Improvement study on influence of plasma electrode edge on emittance of ECR ion source

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In the design of extraction systems for intense ion sources, particularly Electron Cyclotron Resonance (ECR) ion sources, overall configuration of electrodes is the main consideration. However, a detailed aspect has not received sufficient attention, that is, the influence of the front edge of plasma electrode. Near this edge, direction of electric field changes abruptly, causing ions subjected to these electric field forces to move aberrantly, which subsequently increases the emittance of ion beam. The extent of this phenomenon may be underestimated. By chamfering the front edge, emittance is significantly improved. Two types of chamfering have been investigated and both perform well. It is suggested that chamfering be a practical way in designing plasma electrode and improving emittance.

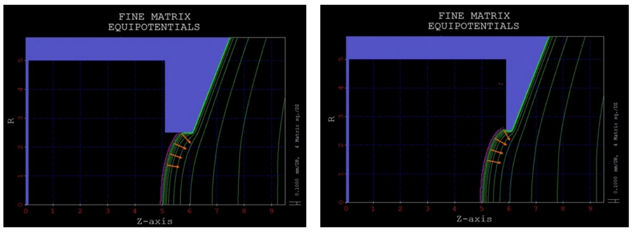
Keywords: ion sources; plasma electrode; emittance improvement; chamfering

I. INTRODUCTION

Studies on improving ion beam emittance are always important in ECR ion source research, and most of them are concentrated on holistic configuration of electrodes and space charge compensation [1–3]. But influence by structural details of plasma electrode may be ignored. In the process of extracting ions from plasma, electric field penetrates into the aperture of plasma electrode, and interacts with plasma to form an emitting sheath [4, 5]. When electric field in the aperture takes low degree of consistency, plasma sheath would deform, thereby increasing the emittance.

The front edge of plasma electrode is the factor to cause that inconsistency of electric field. The front angle of the extracting aperture is usually a right angle or a Pierce angle. This implies that at the front end, there exists an edge where two faces of the electrode intersect with each other, and around which equipotential lines bend dramatically. The front edge, as a part of metal equipotential body, hinders neighboring electric field from penetrating into the aperture. That squeezes equipotential lines and causes distortion to electric fields. Ions in this region subjected to these electric field forces would move towards the central axis at an abnormal angle. See Fig. 1(a). Regardless of whether the electrode aperture is thick or thin, as long as electric fields penetrate into it, this effect occurs. For a thin aperture, electric fields would penetrate into the backside, and be distorted even worse [6–8]. See Fig. 1(b).

This effect has not been systematically discussed, perhaps because the impact is thought to be minimal. An ECR ion source usually uses plasma electrode with an aperture of several millimeters in diameter [9], which is big enough that electric field would penetrate into the aperture directly. The plasma boundary is formed in the aperture and this phenomenon does exist in intense ion sources. Sometimes people want to get a sufficiently convergent ion beam to compensate for space charge effect by increasing extracting voltage. In these cases, electric fields penetrate more deeply into the aperture, and this phenomenon can be even prominent, and may be the reason of hollow beams.



(a) (b)

Fig. 1. (a) In the adjacent area of the front edge of a plasma electrode with Pierce angle, ions subjected to distorted electric field forces move at an abnormal angle towards the axis; (b) when the aperture is thin, electric fields penetrate into the backside of the aperture, and ions move at an even more abnormal angle. Yellow arrows indicate the moving directions of ions.

II. PHYSICAL ANALYSIS

Formation of plasma boundary, or the so-called meniscus, is a result of interaction between plasma and electric field. The shape of meniscus depends on density of plasma and strength of electric field. With strong electric field and low density of plasma, a more concave meniscus is obtained, and vice versa [10]. Around the rear side of the front edge, electrostatic shielding takes place near the inner wall, thereby weakening the electric field strength. With a weaker electric field, plasma diffuses ahead along the inner wall of aperture. Consequently, the periphery of meniscus is elongated. That means the curvature of meniscus would change at an uneven slope near the front edge. Ions emitted from this part of meniscus would move in different directions and cannot be well focused, resulting in an increase in emittance.

Another effect can even aggravate the situation. Let's take a look at the simulation result of electrostatic field distribution without any plasma in the extracting system. As the plasma electrode is an equipotential body, directions of electric fields

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are perpendicular to the inner wall of the extracting channel. See Fig. 2. When there is plasma in the aperture and ions from plasma are approaching the inner wall, electric fields make them move towards the central axis of the system. At the periphery of meniscus where plasma density is low, this effect plays a role. It exacerbates the meniscus aberration.

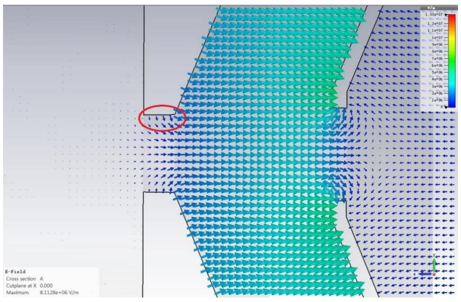

Fig. 2. Directions of electric fields in the extracting system; circled in red are those near the inner wall of plasma electrode aperture.

III. SIMULATION RESULTS

Based on the above analysis, some approaches are explored to mitigate this effect. PBGUNS codes are used to simulate our modified models. The aperture cannot be overly thin; in other words, it must have a certain thickness, as mentioned in Section 1, to prevent electric field from penetrating into the backside of the aperture and becoming more distorted. Here, we do not take into account the density variation of plasma with aperture depth, as we just discuss the effect caused by the front edge. The front edge, as a point of mutation, should be weakened to reduce its interference with electric fields. In order to focus on the issue, we simulate extraction system consisting of two electrodes, to make things clear. The parameters of the extraction system are listed in Table 1.

Table 1. Parameters of the extraction system.

Parameter	Value
Diameter of plasma electrode aperture (mm)	5
Thickness of plasma electrode (mm)	1
Diameter of pulling electrode aperture (mm)	7
Thickness of pulling electrode (mm)	1
Gap between two electrodes (mm)	10
Extraction voltage (KV)	30
Ion current (mA)	20

A direct approach is to trim the front edge to make a chamfer. A 45-degree straight chamfering is made as an attempt. Emittance is read at a target 83.7mm from the extracting aperture. Negative hydrogen ions are extracted. Simulation results show that RMS emittance is improved from $1.859 \times 10^{-1}\pi mm\cdot mrad$ to $5.709 \times 10^{-2}\pi mm\cdot mrad$. It can be observed that the initial beam has a gap in the middle and scatters in the outer ring, as circled by the orange dashes in Fig. 3(a). After chamfering, beam distribution becomes more concentrated, as circled in Fig. 3(b).

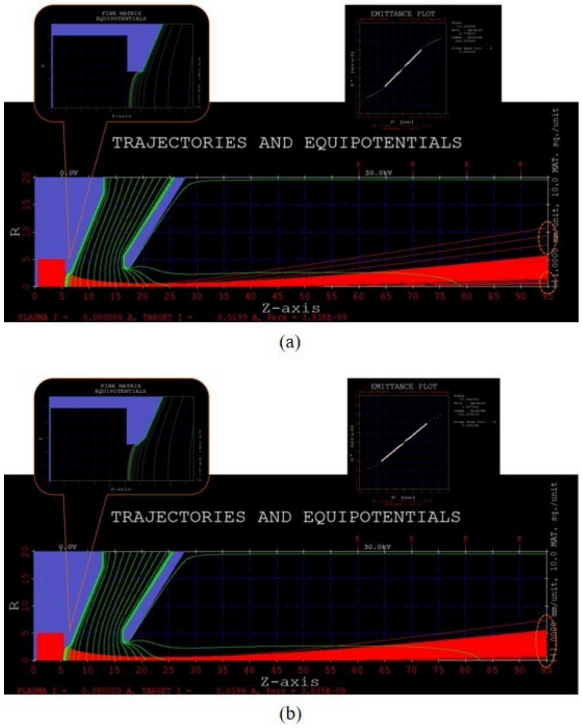

Fig. 3. (a) the simulation with a sharp front end; (b) the simulation after 45 degrees chamfering.

Chamfering can be done linearly or circularly, with different incline angles, lengths, and arc radii. The impacts of these parameters on emittance are investigated. We make straight chamfering with different angles, including 10, 20, 30, 35, 40, 42, 45, 50, 60 degrees. The inner one endpoint of the straight chamfering is fixed at $0.3mm$ deeper than the original front point, while the outer endpoint moves as degree changes. Fig. 4 shows the emittance variation with chamfering degrees.

We observe that, for most angles, emittance is reduced to approximately one-third of the original value. Best emittance improvement is achieved around 40 degrees chamfering. With the two largest and smallest angles, emittance does not improve significantly. This is because when chamfering angle is small, the front edge just moves upwards a little bit, and its influence on the electric field has not been reduced sufficiently. When chamfering angle is large, electric field penetrates through the chamfering to the extracting aperture and interacts with plasma, making the emitting surface move inwards. The inner endpoint takes the position of former front edge as a new mutation to distort the electric field. Then, the situation is similar to that without chamfering.

With circular chamfering, as radius varies from $0.3mm$ to $2.2mm$, the emittance achieves best improvement at around $1.5mm$. See Fig. 4. When radius is small, electric field distribution does not change obviously, just like without chamfering. As radius grows, the chamfering effect becomes to work,

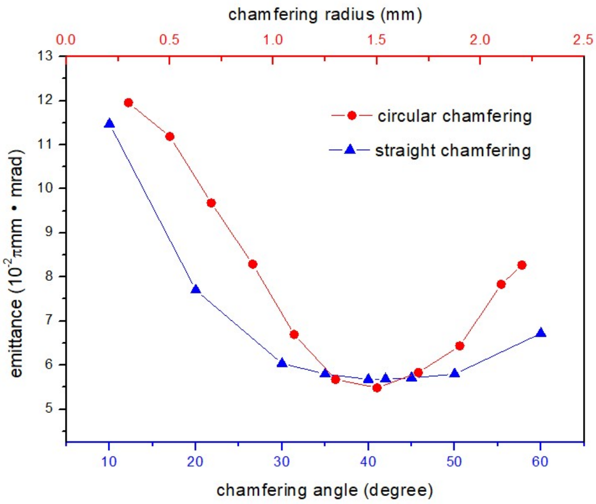

Fig. 4. Emittance varies with chamfering angles and radii.

and the emittance decreases. When radius gets too large, the circular front surface compresses electric fields, and the front edge effect begin to play a dominant role, resulting in an increase in emittance.

We can see that, both straight and circular chamfering, with appropriate angles or radii, can mitigate the influence of front edge. Straight chamfering can lower emittance obviously in a relatively wide range of angles. Circular chamfering lowers emittance within a narrow range of radii, but the most optimal emittance improvement is obtained with it. It's difficult to assert that circular chamfering is superior to straight chamfering, or the converse, as it requires systematic investigation under more conditions.

When we perform the chamfering while fixing the inner endpoint $0.3mm$ deeper than the original front point, it implies that the spacing between the inner endpoint and the puller electrode is $0.3mm$ larger than the previous gap between the two electrodes. It cannot be excluded that the increase of this gap weakens the electric field and alters the emitting surface. Therefore, we move the puller electrode $0.3mm$ forward respectively after chamfering 30, 40, 50, 60 degrees to offset the increased spacing. Results in Fig. 5 shows that emittance still gains obvious improvement compared to the original $1.859 \times 10^{-1}\pi mm \cdot mrad$.

IV. DISCUSSION

Moving puller electrode forward by the same distance as front point retraction actually shortens overall spacing between plasma electrode and puller electrode. Even so, the emittance decreases significantly after chamfering. This demonstrates that chamfering is indeed an effective way of reducing emittance. The physical mechanism behind it is that electric field near the surface, especially a bending surface, of a conductor is typically much stronger than at other locations of the field. Thus, in our case, the front edge exerts a

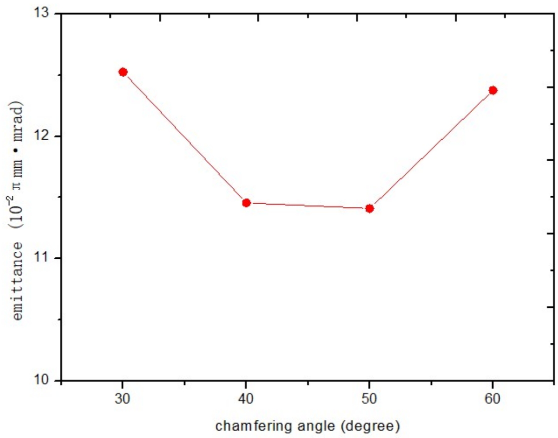

Fig. 5. Emittance after chamfering and moving puller electrode forward.

considerable influence on the moving directions of ions. This emphasizes the importance of trimming the front point.

Other structures of plasma electrode, such as the stepped electrode, can also be regarded as a type of chamfering and play a role in reducing emittance. However, its front surfaces change more rapidly and bring about a more severe mutation of electric field. Backside chamfering is also not advisable for the same reason as thin electrode. We will not extend the discussion. Here, we just illustrate that emittance can be improved by chamfering.

Extraction voltage, ion current, and ion species are not, nor do they need to be, carefully selected and optimized in our model, but are sufficient to demonstrate the issue.

V. CONCLUSION

The study regarding the effect of extraction system on emittance of ECR ion sources has always been focused on the overall configuration of electrodes. However, we put forward the point that the front edge of electrode also has a great influence on emittance. Based on physical analysis, by chamfering the front edge, we can notably reduce the emittance. The two types of chamfering that we tried can both improve the emittance. It indicates that chamfering can be a useful way in designing extraction electrode. Future work we need to undertake is to conduct experiments for comparison with simulations. That needs emittance measuring equipment which we do not possess at present. The states of plasma and meniscus after chamfering are also important aspects that we are going to investigate.

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